THE VALUE OF CERTAIN CRITERIA FOR THE DETERMINATION OF THE ORIGIN OF FOLIATED CRYSTALLINE ROCKS. I

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OUTLINE

[1] By "primary gneiss" the writer understands a banded crystalline rock of igneous origin whose banding was produced prior to the complete solidification of the rock.

PART I

INTRODUCTION

REVIEW OF CRITERIA PROPOSED FOR THE DETERMINATION OF THE ORIGIN OF FOLIATED CRYSTALLINE ROCKS

Criteria constitute one of the most important divisions of a geologist's working "equipment." While they are needed and are being developed along the whole line of attack on the problems of geology, probably no section of investigators appreciates their value more than that engaged in unraveling the history of foliated crystalline rocks. This seems to be because that subject is particularly many-sided and difficult, for it cannot be said that suggestions as to methods of approach are at all lacking in number. To indicate the range of these proposals, and to give an idea of the state in which the problem stands today, the better known criteria for the determination of the origin of foliated rocks have been collected in the lists which follow. It must be acknowledged, however, that in many cases the results of their application are more suggestive than conclusive.

Criteria for the determination of original igneous or sedimentary character.—The following have been suggested as criteria for distinguishing foliated rocks which were originally sedimentary from those developed from igneous rocks:

Field evidence: *For igneous origin*—gradation into recognizable igneous rocks; preservation of original structures, such as boundaries of a dike; preservation of original textures, such as porphyritic; uniformity over large areas. *For sedimentary origin*—gradation into normal sedimentary rocks; preservation of original structures, such as pebbles of a conglomerate or cross-bedding; regular and continuous banding;[1] intercalation with beds of limestone or quartzite;[2] rusty weathering.[3]

Microscopic evidence: *For igneous origin*—preservation of igneous textures in the less altered portions; presence of minerals characteristically formed only from igneous melts and readily

[1] J. F. Kemp, "Pre-Cambrian Sediments in the Adirondacks," *Proc. Am. Assoc. Adv. Sci.*, XLIX (1900), 167.

[2] *Ibid.*, 174. [3] *Ibid.*, 168.

decomposed during sedimentation, such as nepheline,[1] leucite, etc.; presence of unaltered minerals characteristically formed only from igneous melts and which become modified or segregated during sedimentation, such as zircon and monazite; presence of secondary minerals generally considered to be more characteristic of altered igneous than altered sedimentary rocks, such as epidote, zoicite, chlorite, and hornblende.[2] *For sedimentary origin*—preservation of original fragmental texture;[3] presence of secondary minerals supposedly more characteristic of altered sedimentary than altered igneous rocks, e.g., a group high in Al_2O_3 and low in bases, such as staurolite, andalusite, sillimanite, and cyanite, but also other minerals as biotite, garnet, and graphite.

Chemical evidence: *For sedimentary origin*—variation from normal igneous rock types as shown by comparison with classified tables of igneous rocks arranged according to chemical composition; molecular ratio of Al_2O_3 to Na_2O, K_2O and CaO greater than 1; excess of K_2O over Na_2O by weight; excess of MgO over CaO by weight;[4] high Al_2O_3 content; high SiO_2 content.

Criteria for distinguishing primary gneisses from metamorphic rocks with a banded structure.—Many criteria have been suggested for the recognition of igneous rocks whose foliation was produced during the consolidation of the rock. The importance of this rock class has not been conceded by all geologists, though gneisses have been confidently described as such by Lawson,[5] Geikie and Teall,[6] Bonney,[7] Barlow,[8] McMahon,[9] Weinschenk,[10] Adams and Barlow,[11] and many others. Examples of primary gneisses have

[1] W. H. Emmons, "A Genetic Classification of Minerals," *Econ. Geol.*, III (1908), 620.

[2] C. R. Van Hise, "Treatise on Metamorphism," *U.S.G.S.*, *Mono. XLVII* (1904), 916.

[3] F. Bascom, *Geol. Soc. Amer. Bull.*, XVI (1905), 294–95.

[4] E. S. Bastin, *Jour. Geol.*, XVII (1909), 445.

[5] A. C. Lawson, *Ann. Rep. Geol. Surv. Can.*, N.S. III, (1887), 139 f.

[6] A. Geikie and J. J. H. Teall, *Quar. Jour. Geol. Soc.*, L (1894), 645.

[7] T. G. Bonney, *Q.J. Geol. Soc.*, LII (1896), 17.

[8] A. E. Barlow, *Ann. Rep. Geol. Surv. Can.*, N.S., X, Part 1 (1897), 48–87.

[9] C. A. McMahon, *Geol. Mag.*, N.S., Decade 4, IV (1897), 345–55.

[10] E. Weinschenk, *Congrès géol. inter.*, *compte rendu*, session VIII, I (1900), 326–40.

[11] F. D. Adams and A. E. Barlow, *Geol. Surv. Can.*, Mem. 6 (1910), 83.

most recently been described by Loughlin[1] in Connecticut and Rogers[2] in the state of New York. The following have been suggested as criteria for distinguishing these gneisses from those formed by the alteration of solid igneous rocks:

Field evidence: Banding in apophyses from the gneiss parallel to the walls and at an angle to the schistosity of the inclosing rock,[3] dikes of pegmatite belonging to the same magmatic series as the gneiss and either parallel to the gneissic structure and foliated with it or cutting the gneissic structure and undisturbed; lack of sharp contact between the acidic and more basic portions of the gneiss, indicating high temperature during the solidifications of the different bands;[4] presence of inclusions of foreign rock, which are but slightly deformed, in a matrix of well-banded gneiss;[5] presence of distinct bands of widely different composition, none of which may show evidence of shearing; flowlike curves of the banding, some of which may close in a circle.

Mineralogical evidence: Presence of minerals formed characteristically only from igneous melts and arranged in a manner impossible of formation from solid rocks by metamorphism, e.g., nepheline and olivine; textures due to crystallization from an igneous melt. Weinschenk[6] considers that epidote, garnet clinozoicite, sillimanite, and chlorite crystallize from the magma in the case of primary gneisses on account of the pressure present during the solidification of the rock, but the exact state of the rock during their formation is not definitely known.

SCOPE OF PAPER

In the following thesis only three of the many criteria which have been proposed have been considered. They are (1) the criterion of texture as applied to primary gneisses, (2) uses of zircon as a criterion, (3) use of chemical composition in the deter-

[1] G. F. Loughlin, *Am. Jour. Sci.*, 4th Ser., XXIX (1910), 447–56.

[2] G. S. Rogers, *Am. Jour. Sci.*, 4th Ser., XXXI (1911), 125–30.

[3] J. W. Gregory, *Q.J. Geol. Soc.*, L (1894), 265.

[4] *Geol. Surv. Can.*, Mem. 6 (1910), 83.

[5] *Geol. Mag.*, N.S., Decade 4, IV (1897), 354.

[6] *Congrès géol. inter., compte rendu*, session VIII, I (1900), 340.

mination of sedimentary or igneous origin. It must be remembered, however, that one type of criterion can seldom be employed effectively alone, although the limitation of possibilities obtained by the application of several criteria may lead to evidence that is practically conclusive.

The writer is deeply indebted to Dr. C. K. Leith and other members of the geological department of the University of Wisconsin for assistance and suggestions received during the preparation of this article.

TEXTURE AS A CRITERION FOR THE IDENTIFICATION OF PRIMARY GNEISSES

OUTLINE OF DISCUSSION

In order that the reader may more easily understand the trend of the argument which the writer will advance regarding the value of texture as a criterion for the identification of primary gneisses, the discussion which follows is here summarized.

Milch[1] in a recent article expresses the opinion that igneous rocks with an original foliation should not be included in the group of the "crystalline schists." He regards texture as the most promising criterion so far brought forward for distinguishing these rock classes. It is the suggestion that texture may be used as a criterion for distinguishing primary gneisses from those of metamorphic origin which the writer proposes to examine in the course of the present paper. Milch's idea was that "crystalline schists" are characterized by metamorphic or "crystalloblastic" texture, while gneissic rocks which possess an original foliation have the texture of igneous rocks. In order to get a clearer conception of the differences between these two varieties of texture, the writer will review the main features of metamorphic texture according to Grubenmann,[2] whose recent work marks a decided advance in the study of that subject. The causes underlying the differences between these two types of texture are apparently to be found in variations in conditions of crystallization; in one case solidification

[1] L. Milch, "Die heutigen Ansichten über Wesen und Enstehung der kristallinen Schiefer," *Geol. Rundschau*, I (1910), 49.

[2] U. Grubenmann, *Die kristallinen Schiefer*, I (1904), II (1907).

from a fluid and in the other recrystallization of a solid under differential pressure. Grubenmann considers that the chief expression of these different conditions of crystallization is to be found in the forms or outlines of the mineral constituents.

Unusual development of cleavage faces with consequent production of columnar or platy mineral forms is, according to Grubenmann, one of the most common characteristics of the minerals of "crystalline schists." Wishing to make use of this feature in a discussion of the texture of primary gneisses, the writer will review the causes of the unusual elongated habit assumed by minerals when growing under certain conditions. No mineral seems to exhibit better this capacity for abnormal form development than biotite which, happily also, is one of the most characteristic minerals of primary gneisses. The writer in the following discussion expresses the opinion that the biotite grains in normal igneous rocks are roughly equidimensional in shape, and that the platy forms present in metamorphic rocks and in primary gneisses are the result of crystallization under differential pressure. This would seem to suggest that the texture of primary gneisses must be intermediate between the igneous and the metamorphic types. Microscopic evidence seems to lead to the same conclusion. The writer, however, wishes to point out that from the very character of the intrusion of primary gneisses it is to be expected that granulation and recrystallization have frequently taken place after solidification and that, accordingly, a metamorphic texture cannot be regarded as proof that the banding in a gneiss was not produced when the rock mass was still partially fluid. It is the writer's view, however, that with certain limitations, igneous texture, when present, may be legitimately urged as proof of primary banding.

DISTINCTION BETWEEN IGNEOUS AND METAMORPHIC TEXTURES

By the term "texture" the writer understands the character of a thin section or surface of a rock due to its degree of crystallinity and to the size, shape, and arrangement of its minerals.

Crystalloblastic texture.—The term "crystalloblastic"[1] has been proposed as a designation for the texture of recrystallized rocks.

[1] F. Becke, *Tschermaks Min. petrog. Mitt.*, XXI (1902), 356–57.

Among the characteristics of this texture,[1] according to Grubenmann, are the following:

1. Lens-like and roundish forms of the minerals, well-developed crystal outlines not generally being present. When crystal forms do occur they are generally simple. Foliation of minerals is frequently developed.

2. The relative perfection of mineral form is dependent on the character of the minerals rather than upon their order of crystallization. The usual series of form development is as follows: titanite, rutile, hematite, ilmenite, garnet, tourmaline, staurolite, cyanite—epidote, zoicite—pyroxene, hornblende—magnesite, dolomite, albite, mica, chlorite, talc—calcite—quartz, plagioclase—orthoclase, microcline. In general the series is one of decreasing specific gravity or increasing molecular volume.

3. Marked development of crystal faces which are parallel to planes of mineral cleavage.

4. Characteristic mineral inclusions. In igneous rocks the inclusions are usually well-developed crystals which have solidified early. In the "crystalline schists" the later formed minerals may have more perfect outlines than their inclusions.

5. General absence of zones of different composition in minerals.

6. Holocrystalline character.

7. Tendency toward uniformity in size of grain.

Grubenmann's conception of the causes which underlie the differences in character between the textures of igneous and metamorphic rocks may be outlined as follows: He regards the forms of the minerals in igneous rocks as dependent largely on their order of crystallization, i.e., the earlier formed minerals have good crystal outlines while those of later development, having been compelled to occupy the remaining spaces, are irregular in form. In metamorphic rocks, on the other hand, he considers that the crystallization of all the minerals has been more or less hindered by the solid condition of the rock and that those minerals possess the best developed forms which have the strongest crystallizing force. This "force," Grubenmann regards as greatest in minerals which

[1] Grubenmann uses the word "Strukur" in place of "texture." "Strukur," as defined by him, relates to the form and size of the constituents. "Textur" is used for their arrangement.

have the smallest molecular volume or the highest specific gravity. As an explanation, also, for the unusual development of cleavage faces in certain minerals, he suggests that the molecular arrangement in such minerals is denser within the plane of mineral cleavage than across it. Though the suggestion of parallelism between perfection of crystal form and molecular density is interesting and probably significant, it must not be forgotten that the characteristics of crystalloblastic texture previously enumerated are based almost solely on observation.

Recent opinions on the crystallization of igneous rocks.—Several writers have recently questioned the views commonly held regarding the order of crystallization of igneous rocks. It has been suggested,[1] for example, that in the important class of the diabases the crystallization of the different minerals has been approximately simultaneous. In such cases it might be supposed that the relative development of crystal form was not entirely dependent upon the order of crystallization and that possibly the resulting texture might be confused with the metamorphic type. Thus in graphic granite,[2] where the outlines of the quartz areas agree more or less with the cleavage directions of the feldspars, the relations of the two minerals would seem to be dependent upon the individual properties of the minerals rather than upon their order of crystallization. Notwithstanding such cases of apparent simultaneous crystallization, it will probably be generally agreed that there is no reason yet known for thinking that order of crystallization is not the most important factor in determining the mineral outlines of normal igneous rocks. Grubenmann has pointed out, moreover, that there are important differences between the texture produced by simultaneous crystallization from an igneous melt and that resulting from recrystallization.

THE SIGNIFICANCE OF THE ELONGATED HABIT ASSUMED BY MINERALS WHEN GROWING UNDER CERTAIN CONDITIONS

The development of columnar or platy habit in minerals of a rock is a feature which is controlled by the individuality of the

[1] C. N. Fenner, "The Crystallization of a Basaltic Magma from the Standpoint of Physical Chemistry," *Am. Jour. Sci.*, XXIX (1910), 220.

[2] L. V. Pirsson, "Rocks and Rock Minerals" (1908), 212.

minerals and the conditions present during their formation rather than the relation of the minerals to their order of crystallization. According to the views previously outlined it should be, and actually is, a characteristic of metamorphic rocks rather than normal igneous varieties. As many minerals present in primary gneisses seem to possess an abnormal elongated habit, it is hoped that a discussion of this feature may throw some light on the texture and mode of origin of these rocks.

Elongation of minerals under viscous conditions in an igneous melt.—Pirsson[1] has recently published an interesting article in which the effect of viscosity on mineral habit is discussed. His observations on sections of rocks which have solidified quickly show that the minerals of such rocks tend to assume tabular or needle-like forms. It was especially noted that the elongation is generally parallel to prominent cleavage faces. Pirsson attributes this to the fact that the cohesive attraction within the plane of cleavage is greater than that across it. He supposes that viscosity may become so great that the molecular attraction across the mineral cleavage is insufficient to orient additional material so that the mineral becomes elongated in the direction of its cleavage. The growth of the crystal end, he considers, may be aided by the mobility imparted to the surrounding liquid by the heat of crystallization. Miers[2] has explained somewhat similar cases of elongation of crystals by the supersaturation of the surrounding solution. He considers that the end of the crystal may be able to remain continually in strongly supersaturated solution and, accordingly, grows more rapidly in one direction. This seems to be a somewhat different explanation from that given by Pirsson. While opinions regarding the cause of mineral elongation may vary, the fact that minerals do assume elongated habits when growing under viscous conditions in a magma and that the elongation takes place very frequently parallel to prominent cleavage directions seems to be pretty well established.

Elongation of minerals due to differential pressure.—That rocks which have recrystallized under great pressure are characterized

[1] L. V. Pirsson, "On an Artificial Lava-Flow and its Spherulitic Crystallization," *Am. Jour. Sci.*, XXX (1910), 97.

[2] H. A. Miers, *Science Progress*, II (1907), 128–29.

by a parallel arrangement of mineral constituents is, of course, a fact which is accepted by all writers. Perhaps, however, it is not so generally understood that the shapes of the so-called "platy minerals" of these rocks are generally different from those which the same minerals assume when growing under freer conditions. To illustrate this difference in shape, the writer will discuss the dimensions of quartz, biotite, hornblende, and feldspar in igneous and metamorphic rocks. These minerals were selected because they vary in the character of their cleavage and all are, moreover, common rock-forming constituents.

Quartz is the most common example of a group of minerals which possess no good cleavage. In metamorphic rocks it owes its form in the majority of cases either to granulation or recrystallization. When the grains result from granulation they are generally irregular in shape and roughly equidimensional, but the writer's observations seem to show that those grains which have crystallized[1] under differential pressure are frequently elongated parallel to the plane of rock cleavage. It appears, however, that the ratio of the dimension of the quartz grain in the direction of schistosity to that at right angles to it is seldom greater than two. Generally, also, as Leith[2] has pointed out, there is no relation between the elongation of quartz and its crystallographic directions.

Biotite is a mineral which is characterized by a single well-marked cleavage. Chlorite and sericite, both important rock-forming minerals, are similar to biotite in respect to cleavage. In the following measurements of biotite grains the ratio of the length in the direction of mineral cleavage to that across it has been determined. An average of 167 grains of biotite in 19 sections of igneous rocks showed a ratio of 1.5, but many soda-rich rocks gave average values of about 1.0, and in rocks with porphyritic texture the ratio rose sometimes to 2.0 or even 2.5. In the latter case the rocks have probably crystallized quickly and under somewhat viscous conditions. Similar measurements of biotites in sections of schists generally gave average values above 6, though when the development of schistosity had taken place near an igneous contact the

[1] The criteria for recognizing recrystallized minerals has been discussed by Leith in *U.S.G.S. Bull. 239* (1905), 70–71.

[2] *U.S.G.S. Bull. 239*, 35.

ratios were sometimes lower than this. An average of 46 observations on biotites of the Wissahickon[1] sedimentary gneiss gave a value of 7.2. In all schistose rocks so far mentioned the direction of mineral cleavage and elongation corresponded, in general, with the plane of rock cleavage. When biotites crystallize under mass-static conditions, i.e., in the absence of differential pressure, the form of the biotite grains, as shown in Fig. 4, seems to approach that characteristic of normal igneous rocks. In such cases there is commonly no relation between the direction of mineral elongation and that of rock cleavage. These "porphyritic" biotites may

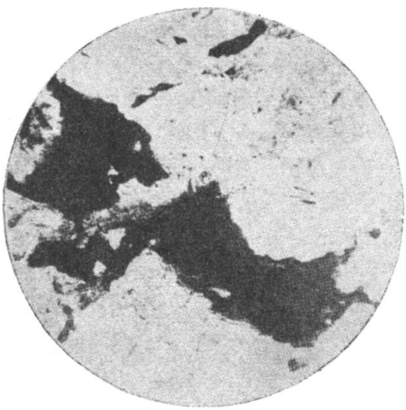

FIG. 1.—Biotites in nepheline syenite. ×32

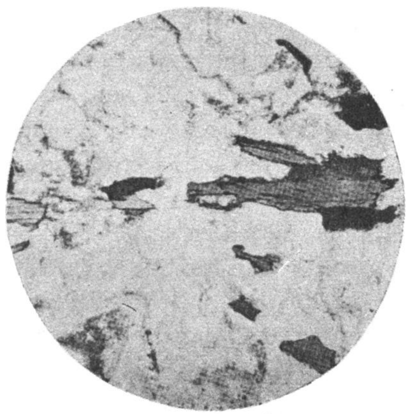

FIG. 2.—Biotites in primary gneiss. ×32

frequently be recognized by the number of inclusions they contain, a feature which is not common in grains which have crystallized under differential pressure. From the foregoing observations it may be seen that a platy form is not always characteristic of biotite, as is sometimes supposed, but that this habit is determined by the conditions of its formation. Such observations as the writer has made indicate that the effect of differential pressure on the forms of sericite and chlorite is analogous to that in the case of biotite.

Hornblende possesses a prismatic cleavage, the angle between the planes being about 124°. Leith[2] has shown that the hornblendes

[1] *U.S.G.S. Folio 162*, 1909.

[2] *U.S.G.S. Bull. 239*, 29.

in a schist are elongated parallel to the prism and that the elongation of the mineral corresponds generally with the direction of rock cleavage. In many cases the longer axes of the cross-sections of the hornblendes were observed to lie approximately in the plane of schistosity. According to Leith[1] the ratio of the greatest to least diameters of hornblende, which in schistose rocks varies from 100:20 to 100:24, ranges in igneous rocks from 100:30 to 100:75 with 100:40 as a common value.

Feldspar possesses various cleavages but those parallel to the base and the side pinacoid are the most pronounced. These two

FIG. 3.—Biotites in schist. ×32

FIG. 4.—"Porphyritic" biotites in schist. ×32.

cleavages are approximately at right angles to one another. Leith[2] has stated that in schistose rocks the parallelism of the feldspar particles is not close and that rarely the parallel arrangement is also crystallographic. The writer's observations on similar rocks indicate that feldspar grains are occasionally elongated in the direction of rock cleavage but no relation was noticed between the elongation and the crystallographic directions of the grains.

Conclusions regarding the causes of mineral elongation.—It has been noted that under certain conditions minerals tend to assume an abnormal elongated habit. High viscosity or strong super-

[1] *Op. cit.*, 30–31.

[2] *Op. cit.*, 40.

saturation and differential pressure appear to be the most important of these conditions. In either of these cases the resulting form of the mineral seems to depend to a marked degree upon the character of its cleavage. The elongation of quartz, on the other hand, a mineral which possesses no good cleavage, is, under differential pressure at least, not marked and is apparently independent of crystallographic directions. The only possible exception noted to these generalizations is feldspar. While feldspars crystallized from viscous melts are, apparently, elongated parallel to the two principal cleavages, in the grains formed under differential pressure there does not appear to be any relation between the direction of elongation and the position of mineral cleavage. This is possibly to be explained by the number of cleavage planes in that mineral or to the position of the two principal cleavages at right angles to each other.

Pirsson[1] has explained the development of mineral elongation in viscous melts by differences in molecular attraction which are considered to exist between directions within and across the cleavage. Since the same forces act during the normal crystallization of minerals, this might lead one to think that the elongation of crystals due to the conditions of the solution or to differential pressure represented only a more pronounced development of differences in dimensions existing in crystals of normal development. That this is not so, and that the elongation of minerals which have developed under favorable conditions may be independent of mineral cleavage is shown by the well-known prismatic crystals of quartz, found so frequently in cavities, notwithstanding the fact that quartz is a mineral which possesses no good cleavage. It seems a more general rule that uniaxial minerals, when freely developed, are elongated in the direction of the vertical axis, no matter what the direction of mineral cleavage. Apatite, beryl, and corundum, for example, appear to be all normally elongated at right angles to their best plane of cleavage. The same is true for the orthorhombic minerals topaz and danburite. Among rocks, pegmatites probably offer the most favorable conditions for the development of biotite crystals and here they are frequently, if not generally, elongated at right angles to their cleavage.

[1] *Am. Jour. Sci.*, XXX (1910), 110.

To the writer, the conception of differences in molecular attraction within and across the cleavage of a mineral seems to afford a plausible explanation why the elongation of minerals under unfavorable conditions for growth takes place parallel to the plane of mineral cleavage. This idea, though, is of course purely speculative. There may be also reasons, not at present known, which would cause minerals, such as biotite, to be more stable under conditions of differential pressure when lying with their planes of cleavage parallel to the greatest pressure. It is almost useless to conjecture what causes the normal elongation of some minerals at right angles to their cleavage, though one might suggest molecular form or arrangement as possibilities.

Inferences regarding the texture of primary gneisses from mineral elongation.—Descriptions of primary gneisses seem to show that a more or less parallel arrangement of platy mineral constituents is a constant characteristic of this rock type. This arrangement may be considered to have been caused by (1) rotation of minerals in a still fluid magma, by (2) development of abnormal elongated mineral forms during crystallization, by (3) parallel growth of minerals with normal form development, or by (4) granulation, slicing, or gliding. The first method would probably give rise to characteristic igneous textures. Microscopic studies of schists indicate that the last three processes would tend to the production of the metamorphic type of texture.

The writer has endeavored to point out in preceding sections that the development of abnormal elongated mineral forms is an important feature in the production of schistosity in metamorphic rocks. The following review of the most abundant minerals of primary gneisses is intended to show that this process is also a leading one in the crystallization of primary gneisses and, accordingly, that the texture of such rocks must have some of the characteristics of the metamorphic type.

Among the minerals most frequently mentioned as having been rotated in a magma is *biotite*.[1] The following points seem to indicate, however, that in the case of this mineral rotation must be of secondary importance and that its orientation is largely due to the

[1] E.g., *Geol. Mag.*, N.S. (Decade 4), IV (1897), 348.

growth of unusually elongated grains parallel to the direction of least pressure.

1. The measurements previously given indicate that biotites which have crystallized slowly from igneous melts are not platy in the majority of cases, and that before being interfered in crystallization by other minerals they were not far from cubical in form. The orientation of such grains in a fluid magma must then be almost impossible.

2. The extremely irregular outlines of biotites in normal igneous rocks suggest that biotites do not generally crystallize much in advance of the quartz and the feldspar so that completely formed biotite grains cannot be considered to have been ever floating loosely in a fluid magma.

3. Measurements made of biotite grains in a gneiss, which is considered by the writer from field evidences to possess original banding, gave values of from 2.5 to 5.0 for the ratio of the length in the direction of mineral cleavage to that across it. As similar tests on igneous rocks usually gave values from 1 to 1.7 it can be seen that the elongation of biotite is in this case decidedly greater than that characteristic of deep-seated igneous rocks which have solidified under quiet conditions.

4. There seems no reason to think that the biotites of primary gneisses have crystallized under viscous or strongly supersaturated conditions since such rocks are generally of deep-seated origin and probably contained abundant water when in the fluid state.

Elongated *feldspar* grains have been described as having been formed during original crystallization in the Twilight[1] gneissoid granite of Colorado. In this rock the feldspars in the more foliated portions occur as elongated anhedra, while in places where the rock is more massive they possess crystal outlines. In the former case the direction of elongation seems to be unrelated to the crystallographic directions of the mineral.

The elongation of *quartz* has also been observed by the writer in thin sections of the biotite gneiss previously mentioned as exhibiting primary banding.

One who grants that pressure can be sufficiently active during

[1] W. Cross, E. Howe, J. D. Irving, W. H. Emmons, *U.S.G.S. Folio 131* (1905), 7.

the crystallization of primary gneisses so as to cause the development of elongated forms in the minerals must also expect to find in the texture of these rocks many other features common to the metamorphic type. It must be supposed, for example, that along with marked development of cleavage faces would be a general tendency toward the series of form development characteristic of "crystalline schists" as outlined by Grubenmann. The writer's observations seem to corroborate this. In short, the texture of primary gneisses appears to be intermediate between the igneous and the metamorphic types, being more like the latter according as the movements producing the banding continued late in the period of consolidation.

CONCLUSIONS REGARDING THE TEXTURE OF PRIMARY GNEISSES FROM THE MODE OF THEIR INTRUSION

Various types of rock bodies have been described as possessing an original banding and it is natural to suppose that the methods of their intrusion must differ considerably. The size of the bodies varies from dikes, such as are characterized by parallel feldspar phenocrysts, to masses of batholithic proportions. In the case of many of such dikes it can hardly be doubted that the foliation was produced by movements in the magma since the rocks cut by the dikes sometimes show no evidence of rock flowage. The origin of the banding of the gneiss in certain batholiths, attributed by Lawson and others to movements prior to the complete solidification of the rock seems, however, to be considered more uncertain by many geologists. The identification of this type is, however, more important than that of the smaller bodies and its origin will be considered more fully.

The association of igneous activity and batholithic intrusion with periods of mountain building[1] is well recognized. Those who have described batholithic masses as possessing a primary banding are in general agreement that at the time of the intrusion crustal deformations were active and continued so during the solidification of the igneous mass. The intruded rocks have generally been considered to have undergone rock flowage, and, accordingly, no

[1] R. A. Daly, *Am. Jour. Sci.*, 4th Ser., XXII (1906), 195–216.

matter what the depth, to have been under considerable pressure. Weinschenk has more than any other emphasized the importance of pressure during the intrusion of primary gneisses and suggests as proof the wide schistose zones about such bodies. As showing that these were formed during the intrusion, he states[1] that the schistosity of the contact rocks is generally parallel to the border of the batholith and that tourmaline needles, which he considers were formed by pneumatolitic action, frequently lie across the the plane of foliation and, accordingly, were formed later than the schistosity.

It seems not illogical to assume that the movements which were, apparently, present late in the period of consolidation should have sometimes continued after portions or the whole of the rock had completely solidified. If such were the case there would result considerable recrystallization and granulation so that typical crystalloblastic or cataclastic textures might be superimposed on that resulting from primary consolidation. It follows that the mere presence of a metamorphic texture is no proof that the banding of a gneiss is not of primary origin. When, however, such rocks are characterized by true igneous texture, as would be the case if the movements ceased early in the period of consolidation, there seems no reason why this feature should not be regarded as proof that the banding was of primary origin. The use of texture as a criterion for the identification of primary gneisses seems on the whole, then, to be of only limited application.

THE USE OF ZIRCON AS A CRITERION FOR THE IDENTIFICATION OF THE ORIGIN OF FOLIATED ROCKS

INTRODUCTION

It was noted in the general introduction that the criteria which have been proposed for determining the igneous or sedimentary origin of metamorphic rocks can seldom be employed decisively. This is largely because the evidence used is generally indirect, and its application as proof of original character is frequently dependent upon inferences which have as yet not been shown to be correct.

[1] *Congrès géol. inter., compte rendu*, session VIII, I (1900), 330, 337.

The criterion of chemical composition, for example, has been especially popular, probably because it permits of mathematical expression and is almost free from what is called "the personal equation." Its use, however, is based on a supposition, it being assumed that a rock as a whole undergoes no significant chemical change during the development of foliation.

The use of zircon, on the other hand, is especially attractive since it deals with first-hand evidence, and while its limitations are not yet fully defined they can be determined with no great effort by laboratory research. In brief, the proposal regarding the use of this mineral as a criterion for the determination of the origin of foliated rocks is based on observations which show that zircon is present in nearly all igneous rocks as minute crystals and that it is practically absent from argillaceous sediments, having been concentrated during sedimentation in the arenaceous deposits. During this process, also, the zircons tend to assume a worn and rounded appearance.

Derby[1] was the first to appreciate the possibilities of zircon as a criterion, his article outlining the suggestion appearing in 1891. The method does not seem, however, to have been taken up by many geologists, probably more through a lack of advertisement than from any inherent difficulty or weakness. Important use has been made of zircon and the somewhat similarly occurring minerals monazite and xenotime by Derby and his co-workers during active fieldwork in Brazil.[2]

On considering the possibilities of zircon as a criterion, one naturally thinks of such questions as the following: Is the *presence or absence* of zircon sufficiently characteristic of certain rock classes, such as igneous or sedimentary, so that it can be used as a criterion for their recognition after alteration? Is the *character* of the zircon grains in different rocks sufficiently distinctive in order that it may serve to identify them? Do zircon grains ever form or recrystallize during the development of foliation?

[1] C. A. Derby, *Proc. Rochester Acad. Sci.*, I (1891), 202.

[2] It was from Dr. Leith, who has recently had the opportunity of observing the methods of the Brazilian geologists, that the writer received the suggestion to investigate this subject.

Since the answers to the first two questions involve a knowledge of the stability of zircon the third will be considered first. Preceding this, however, a short review will be given of the methods used in the identification of this mineral.

IDENTIFICATION OF ZIRCON

Separation from other constituents.—While zircon is very widely distributed in rocks, it is not usually present at any time in more than minute quantities, indeed generally under 0.4 per cent. For study, accordingly, the zircons in a rock must be concentrated in some way. Derby[1] has recommended that the grains be separated from the ground powder by washing in a Brazilian miner's pan, which, as described, should be made of thick sheet copper in the shape of a broad cone, with sides meeting at the apex at an angle of 120°. Twelve inches is suggested as a suitable diameter of the pan at the opening. The residues obtained, Derby states, may be further separated, when necessary, by means of heavy solutions as Thoulet's or Klein's or with the electromagnet. H. Thürach,[2] in carrying out a valuable and extensive series of tests for the purpose of determining the distribution of zircon, anatase, brookite, pseudobrookite, and other minerals, employed a porcelain dish instead of a copper pan. The writer has examined a considerable number of rocks in the way recommended by Derby and found the method very satisfactory. It was considered advisable to pass the powder through a sieve before panning. The screen generally used was one of 60 mesh. In each case a sample of the concentrate was mounted in Canada balsam similarly to a rock section.

Identification.—The work of Thürach and Derby has shown that minute grains of zircon can usually be easily and surely distinguished from all other minerals except xenotime and cassiterite by ordinary optical methods. The following summary of the characteristics of zircon, except when otherwise stated, has been taken from the work of Thürach.

1. Crystal form.—Rounded grains and well-developed crystals of the tetragonal system. The crystals are usually bounded by

[1] *Proc. Rochester Acad. Sci.*, I (1891), 198.

[2] Würzburg, *Phys.-Medic. Gesellsch.*, XVIII (1884).

some combination of prismatic and pyramidal faces, the former, however, being almost always present. In Fig. 8, representing zircons of the Butte granite, basal pinacoids may be recognized but this, apparently, is not a common development. It was noted by the writer that the cross-sections of zircons are generally oblong rather than square.

2. Twinning.—Twinning in microscopic grains has never been with certainty recognized by Thürach. The writer's experience has been similar. Geniculated twins were observed by Derby in the granite from Somerville, Me.

3. Zonal banding.—Frequent.

4. Color.—In fresh crystalline rocks almost always colorless. The writer has observed grains considered to be zircon which were slightly brownish.

5. Optical characters.—High refringence. Brilliant interference colors of high order, usually red and green, less commonly yellow or blue.

6. Inclusions.—Numerous. Considered by Thürach to consist of apatite, fluids, or gases. Derby states that xenotime also exists as inclusions.

Rutile has been mistaken for zircon but can be distinguished by its color (yellow, yellowish or reddish brown), pleochroism, twinning (common), absence of inclusions, and chemical reactions.

Xenotime was not described by Thürach. From the observations of Derby[1] the usual crystal form appears to be octahedral. It may be identified by the erbium line in the spectroscope or by chemical means.

The writer has not observed cassiterite in microscopic crystals. It is undoubtedly much more limited in its distribution than zircon but when present may be difficult to distinguish from the latter. According to Lacroix[2] cassiterite is more frequently twinned than zircon. It is also generally darker in color. Gaubert[3] states that it can readily be distinguished from zircon by color reactions with organic substances.

[1] *Mineralogical Mag.*, XI (1897), 304–10.

[2] A. Lacroix, *Minér. de la France*, III (1909), 207.

[3] Paul Gaubert, *Bull. soc. fran. minér.*, XXXIII (1910), 326.

THE FORMATION OF ZIRCON AND ITS CAPACITY FOR RESISTING ALTERATION

Crystallization from a magma.—Microscopic evidence shows beyond any doubt that the minute zircons (they are rarely over 0.5 mm. in length) which seem to occur in nearly every igneous rock have in general crystallized as an original constituent. Moreover such methods as are in use for determining the order of crystallization of minerals indicate that zircons have usually formed very early in the consolidation of the magma.

Formation in rocks secondarily through the agency of water or gases.—Derby[1] was of the opinion that all zircons in rocks have resulted from the crystallization of igneous melts and that they could not be formed in a rock secondarily. He argues: "Unless, therefore, these rare chemical agents are introduced into the mass subject to metamorphism by the action of the so-called mineralizing agents (as fluorine, boron, and tin are supposed to be in the formation of tourmaline, topaz, and cassiterite), it is difficult to conceive how the minerals in question can appear as newly formed elements in a metamorphosed sedimentary. Their early crystallization and uniform distribution in eruptives, as well as their absence from schists metamorphosed by contact (in the rare cases in which zircon has been noticed it may be presumed to have existed in the original sediment) exclude the hypothesis of such an introduction."

Thürach, on the other hand, was of the opinion that zircons could form from watery solutions and cited as proof the zircons which occur in druses in the chlorite schist of Tyrol and also the well-developed crystals in the sericite schist of Taunus which is associated with a quartzite containing well-rounded grains. There is just a possibility, however, that in the latter case the sericite schist may have been formed from material which was not as well sorted as the underlying quartzite and consequently more easily rendered schistose. In such a case one would not expect the zircons to be as water-worn as in the purer variety.

The following two cases which have recently come to the writer's attention furnish additional proof that the views expressed by Derby must be considerably modified. In the crystalline lime-

[1] *Proc. Rochester Acad. Sci.*, I (1891), 203.

stone of Grenville,[1] Ont., large crystals of zircon with well-developed faces have been found. They are associated with graphite, wollastonite and titanite and were probably formed through the action of intrusives. The evidence here seems to show that zirconium is capable of being carried in solution some distance from the main body of the intrusive.

At Rib Hill, Wausau, Wis., there is a quartzite which is cut by granite and which contains abundant zircons, many of which exhibit

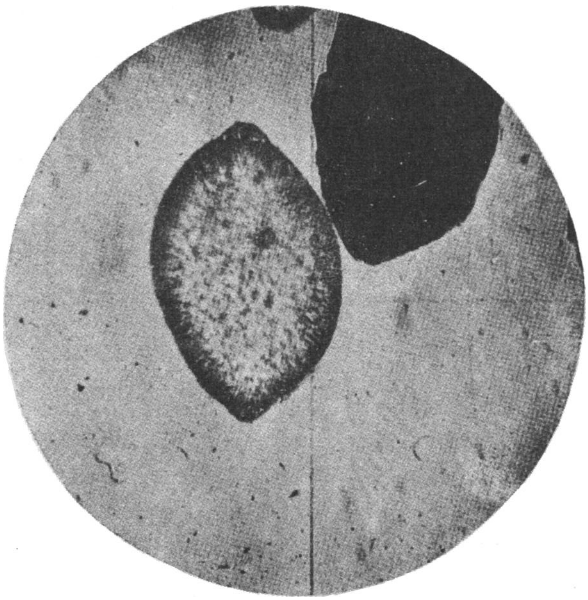

FIG. 5.—Secondary enlargement of zircon. ×180

secondary enlargement. A microphotograph of one of these grains is shown in Fig. 5. The new material has been added largely to the ends of the grains, usually forming pyramidal faces terminated by the basal pinacoid, though the latter is sometimes absent. In one case the new growth was observed to completely envelop the original grain. This suggests that the material for the later crystallization was, in part at least, introduced from without and field relations seem to point to the granite as the source.

[1] C. Hoffmann, *Ann. Rep. Geol. Surv. Can.*, IV, N.S. (1890), 66T.

The capacity of zircon to resist alteration.—To one who cannot see any virtue in the use of zircon as a criterion, if this mineral can be formed in a rock secondarily, the evidence given in the last section must certainly be disappointing. If the reader, however, is willing to accept a compromise and appreciate the value of a mineral as a criterion which is markedly characteristic of certain rock types, widely distributed, and which remains practically unaltered in a rock long after the commoner constituents have

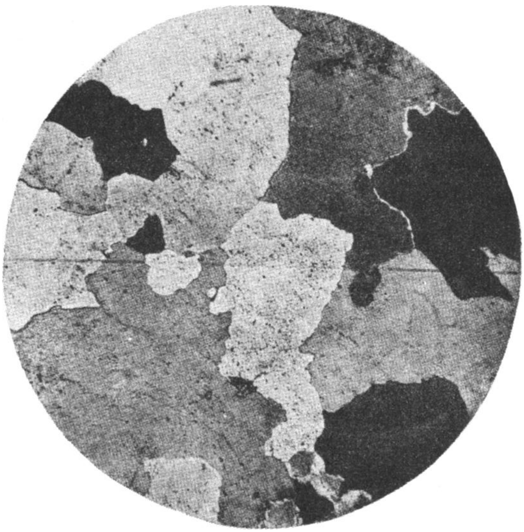

FIG. 6.—Rib Hill quartzite. Crossed nicols. ×20

entirely recrystallized perhaps there is no reason why he should not regard the method as one of distinct promise.

To illustrate: Take the case of the Wausau quartzite which contained the zircons with secondary enlargement. The quartz has here undergone such extreme recrystallization that ordinary evidence of clastic texture has been entirely destroyed. The rock, indeed, is almost as vitreous as ordinary vein quartz. A microphotograph of a section of this rock is shown in Fig. 6. Fig. 7 represents zircons taken from the same specimen as the slide illustrated in Fig. 6 and shows their round and well-worn appearance, a feature which, as will be seen later, is more or less character-

istic of the zircons in sedimentary rocks. Fig. 7, indeed, shows that, notwithstanding the cases of secondary enlargement, the zircons in this rock have suffered but little alteration.

Other tests made by the writer seem to confirm the view that zircon is remarkably stable under the conditions present during the development of foliation. Three sericite schists, for example, considered to have been developed from quartzite all showed no change in the character of the zircons during the alteration of the

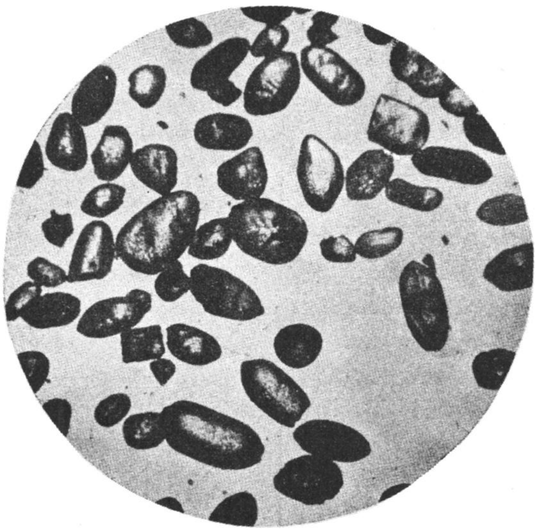

FIG. 7.—Zircon grains from Rib Hill quartzite. ×40

rock. In two of these cases the zircons of both fresh and altered rocks were roundish in form while in the third (illustrated in Figs. 10 and 11) they were somewhat better developed. Two quartzose phases of highly altered sedimentary gneisses showed abundant and well-rounded zircons. In two cases of schist developed from igneous rocks the zircons in the schists were similar to those in the unaltered rocks and possessed sharp crystal outlines.

THE SIGNIFICANCE OF THE PRESENCE OR ABSENCE OF ZIRCON IN A ROCK

Distribution of zircon in unaltered rocks.—Leaving aside for the moment the question of the stability of zircon, one may inquire

regarding the distribution of zircon in unaltered rocks for this, indeed, must form the basis for the application of zircon as a criterion.

Thürach stated that he had recognized zircons in every igneous rock tested, including basalts and dolerites. His observations indicate, however, that they are most abundant in the acidic types such as granite and syenite. Derby, also, has expressed the opinion that zircons are almost universally present in eruptives. Zircons were recognized by the writer in every granitic rock examined but their abundance was found to vary greatly with specimens from different localities. They appeared to be much less numerous in basalts and other basic rocks than in the acidic varieties, none, for example, being detected in a test on material from a specimen of diabase from Gowganda, Ont.

Zircon appears to be present in varying amounts in practically every *arenaceous* rock. Thürach reported its presence in every sandstone examined and the writer's observations are similar, eight quartzites all showing zircon and generally abundant.

Shales, however, appear to be comparatively free from zircon though Thürach's thorough tests revealed its presence in nearly every case examined. Derby says that zircon is almost absent from argillaceous deposits and they were only observed occasionally in such rocks by the writer.

Distribution of zircons in metamorphic rocks.—Thürach found zircon to be generally abundant in feldspar-rich gneisses (presumably largely of igneous origin) and less common in, but seldom absent from, mica gneisses (probably mostly of sedimentary origin). Derby's observations show that schists free from quartz such as amphibolite and amphibole schist frequently show abundant zircons but that micaceous schists contain only comparatively few grains of that mineral. The writer's observations, as was mentioned before, indicate that zircons undergo but little change during the development of foliation in a rock.

On the whole, then, it appears that the examination of metamorphic rocks does not reveal any differences in distribution of zircon than might be expected from the preservation of original grains.

Conclusions.—The facts at hand seem to show that when zircon is present in a rock in considerable abundance the original rock was probably either igneous or a sandstone and not an argillaceous rock or a chemical deposit.

The absence of zircon in a rock is not so significant. It, however, favors the idea that the original rock was of sedimentary origin and suggests somewhat strongly that it was not a granitic rock or a sandstone.

THE SIGNIFICANCE OF THE CHARACTER OF THE ZIRCON GRAINS IN FOLIATED ROCKS

The rounding of the crystal outlines during sedimentation.—It has been previously noted in a general way that the zircon grains in igneous rocks have well-developed crystal outlines while those in sedimentary rocks are more or less rounded. The facts of observation should, however, be stated more fully in order that the amount of confidence to be placed in this distinction as a criterion can be determined.

Thürach has stated that the zircons in granites and syenites generally show well-developed crystal forms while many roundish grains occur in diorite. In basalts and dolerites he observed that the zircons were generally roundish and frequently showed a zonal banding parallel to the boundaries of the grain. In sedimentary rocks, according to Thürach, the zircons are generally rounded but some possess distinct crystal boundaries.

While Derby has noted that the crystal forms in igneous rocks are, as a rule, better developed than those occurring in sands, he has expressed the opinion that in the former perfectly sharp-angled crystals are the exception rather than the rule and apparently characterize the amphibolitic rather than the micaceous types.

The investigations of Mackie[1] on the rounding of sand grains indicate that zircon is more readily rounded than quartz, probably on account of its higher specific gravity. Four sands discussed by this writer showed a predominance of rounded forms in each case.

[1] Wm. Mackie, *Trans. Edinburgh Geol. Soc.*, VII (1897), 298–311.

The recent article by Scherzer[1] on the recognition of the types of sand grains is interesting in this connection. Scherzer considers that well-rounded grains are typical of eolian deposits. In this paper reference is made to the experiments of Daubrée which seemed to show that granules less than 0.1 mm. in diameter[2] cannot be rounded by water action. Typically rounded grains of zircon were observed by the writer in the section of zircons illustrated in Fig. 9 under .06 mm. in diameter.

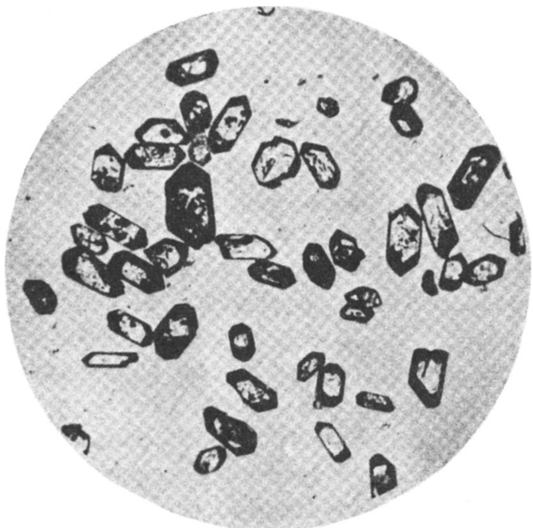

FIG. 8.—Zircons from Butte granite. ×40

The writer's tests indicate that the zircons of granitic rocks have generally good crystal form, sometimes with perfect faces as shown in Fig. 8 and in other cases having somewhat rounded outlines. The zircons represented in Fig. 8 are, by the way, from a biotite granite and form an exception to the rule proposed by Derby with regard to the relative perfection of form between the amphibolitic and micaceous types. Tests made on about 15 specimens of

[1] W. H. Sherzer, *Bull. Geol. Soc. Amer.*, XXI (1910), 625–62.

[2] V. Ziegler in an article which has just appeared states that it is improbable that grains less than 0.75 mm. in diameter could be well rounded under water (*Jour. Geol.*, XIX [1911], 654).

rocks derived from sand showed that the zircons were generally more rounded than is usual in igneous rocks.

From a consideration of the above facts, it must be acknowledged that the zircons in igneous rocks are sometimes roundish in character and that in sedimentary rocks, if the original materials were not subjected for considerable time to the abrasive and sorting action of rivers, waves, and wind, perfect crystal forms may have been preserved. Notwithstanding these possibilities it seems safe

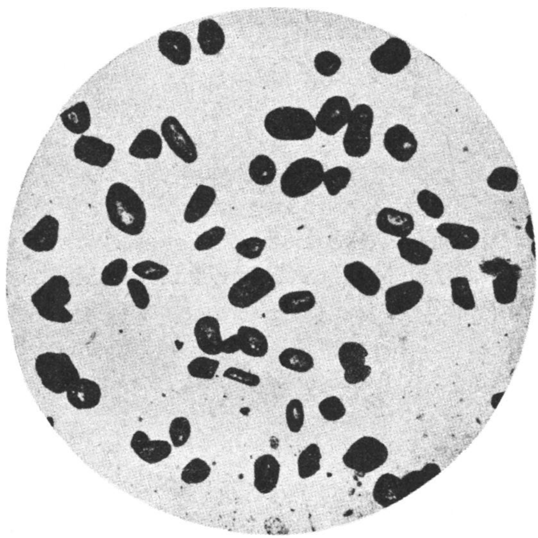

FIG. 9.—Zircons from quartzite, Gowganda, Ont. ×40

to say that the presence of good crystal outlines in zircons of a foliated rock indicates that the original rock was probably igneous while rounded forms suggest a sedimentary origin. When the rounding is pronounced the proof of sedimentary character is strong, but when it is slightly developed it is of little significance.

The luster of zircons in igneous and sedimentary rocks.—The luster of zircon grains is a character closely allied to their form. According to the writer's observations the zircons in igneous rocks usually have a clear, fresh, vitreous appearance while those in sedimentary rocks frequently have a dull, pitted look like ground

glass. Derby[1] has noted this distinction and remarked that "a lack-luster aspect without evidence of alteration is the most certain sign of wear." This dull appearance of the grains is brought out fairly well in Fig. 7.

While it is true that a fresh appearance, like good crystal form, may be preserved during sedimentation, the writer regards this feature as of considerable value as an additional proof of igneous or sedimentary origin.

The significance of peculiar crystal forms.—The zircons in many rocks possess distinct individuality in their forms and the writer considers this peculiarity may be made use of in determining the origin of foliated rocks. It sometimes happens, for example, that near an area of schistose rocks there are other rocks of less altered character which, according to field relations, might well represent part of the original rock, now largely schistose. It is the writer's opinion that zircons in the fresh and altered rocks might be so similar in character as to be fairly conclusive evidence that the two rocks were originally of the same character.

The variation in form depends largely upon the relative development of the different possible faces. Sometimes the zircons are needle-like in character with the prismatic faces prominent, and at other times the crystals may be short and terminated by one or more sets of pyramids. The basal pinacoid face seems to be only rarely developed[2] but is present in the majority of grains in the section made from the Butte granite and illustrated in Fig. 8.

This use of peculiar crystal forms has been tested by the writer successfully in several cases where the fresh and unaltered representatives of a rock were obtainable.

CONCLUSIONS REGARDING THE USES OF ZIRCON AS A CRITERION

1. The presence of abundant, minute grains of zircon in a metamorphosed rock strongly indicates that the original rock was either igneous or an arenaceous sediment. A recomposed igneous rock could in no way, of course, be distinguished from an igneous one by means of this mineral. The possibility of introduction from

[1] *Proc. Rochester Acad. Sci.*, I (1891), 202.

[2] J. D. Dana, *Descriptive Mineralogy* (1909), 483.

igneous contacts must also be kept in mind, though, as was stated, cases where minute zircons have been clearly introduced at contacts are not known.

2. Abundant grains of well-crystallized zircon, especially when uniform in character and fresh in appearance indicates that the original rock was igneous. There are, however, the possibilities of recrystallization of the zircons in an arenaceous sediment during dynamic metamorphism, introduction near igneous contacts and preservation of crystal form during sedimentation.

3. Abundant grains of well-rounded zircon, especially when possessing a worn appearance like ground glass strongly indicates a sedimentary origin. Zircons, however, occur quite frequently as roundish grains in igneous rocks, being especially common in the more basic types.

4. Absence of zircon grains in quartzose bands in a metamorphic rock indicates that such bands do not represent sedimentary layers but were probably deposited from solution.

5. Similarity in character of zircon grains may be used in identifying the unaltered equivalent, when such exists, of the metamorphic rock. Derby has employed this method in Brazil in mapping the distribution of badly weathered rocks.

THE USE OF MONAZITE AND XENOTIME AS CRITERIA FOR DETERMINING THE ORIGINAL CHARACTER OF FOLIATED ROCKS

Monazite (Ce, La, Di), PO_4, has been mentioned by Derby as possibly having an application similar to zircon in the determination of the igneous or sedimentary origin of schists and gneisses. Derby[1] has discussed various methods for the identification of monazite in minute grains. In addition to ordinary microscopic tests, microchemical reactions and examination with a hand spectroscope are recommended. Monazite, according to Derby, is almost universally present in muscovite granites and their gneissic equivalents and frequently occurs in biotite granites. Tests so far made by him indicate that it is lacking in the amphibole granites and all other more basic rocks. As in the case of zircon, monazite becomes concentrated in the arenaceous deposits during sedimentation. The

[1] *Am. Jour. Sci.*, 4th Ser., X (1900), 217–21.

value of monazite as a criterion is, however, lessened by the fact that several cases have been observed in which it is clearly secondary in a metamorphic rock. In addition to secondary enlargements of rounded grains, Derby has noted clear crystals containing inclusions of hematite and rutile and, accordingly, almost certainly of secondary origin. Perhaps the chief application of monazite in the indentification of metamorphic rocks will be found in its use as an aid in the recognition of the unaltered phase of a metamorphic rock when the original type still exists.

Xenotime, YPO_4, is somewhat similar in its character and occurrence to xenotime? It has, however, even a more limited distribution than the latter.

[*To be continued*]